ANN based Tensile Force Estimation for PSC Girder using embedded EM Sensor

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Abstract

The tensile force of PS tendons is most important factor for monitoring the structural health state of PSC girder bridges. The PS tendon located inside of PSC girder thus it is hard to apply the conventional nondestructive testing method. To measure the tensile force of PS tendons this study proposed an embedded EM sensor based tensile force estimation method using artificial neural network. The permeability of PS tendons is changed according to the induced tensile force due to its magneto-elastic effect. The embedded EM sensor can measure the permeability change of PS tendons and the tensile force can be estimated using the pattern of permeability. The embedded EM sensor consists of screw thread for connecting with the sheath, oblique end for insulting to the anchorage part, primary coil for generating magnetic field and secondary coil for measuring the magnetization of PS tendons. To verify the proposed method, the experimental study using three down-scaled PSC girder models was performed. The permeability of PS tendons was proportionally decreased according to increase of tensile forces. The artificial neural network was trained using test data to estimate the tensile force of PS tendons using permeability. As a result, the proposed ANN based tensile force estimation using embedded EM sensor could be one of the solution for evaluating the performance of PSC girder.

1 INTRODUCTION

Since the first post-tensioned concrete bridge was built in 1936, the PSC bridges have been widely constructed around the world [1]. However, after the sudden collapse of the post-tensioned concrete bridges, it was found that the post-tension system has long-term risk such as the corrosion of tendons caused by ingress of water and chloride ion into partially grouted ducts [2]. The tensile forces of the prestressing strands can vary due to a variety of losses including instantaneous losses such as elastic shortening, friction, and anchorage set occurring at the time of transfer of the prestressing force, as well as time dependent losses due to steel relaxation and concrete creep and shrinkage that occur after transferring and during the life of the member. Accordingly, the measurement of the tensile force of the tendon becomes very important for long-term maintenance of the bridges as well as for the purpose of design [3-5].

Various non-destructive test methods have been studied to estimate the tensile forces using ultrasonic waves [7], vibrations [8], fiber optic sensors [9] and magnetic sensors [10]. However the conventional test methods are hard to apply actual PSC girder because the PS tendons are located inside of concrete that cannot be accessed. To overcome this limitation, this study proposes the embedded elasto-magnetic (EM) sensor based tensile force estimation method. The embedded EM sensor can be embedded into the PSC girder between sheath and anchorage block as a joint part. In order to verify the proposed method, an experimental study was performed using down-scaled PSC girder model. Furthermore, the artificial neural network was trained for estimating the tensile force using test data and compared with reference tensile forces measured by load cell.

2 ELASTO-MAGNETIC EFFECT FOR ESTIMATING TENSILE FORCE

The elasto-magnetic effect is the interaction of stress and magnetic energy. When applying a magnetic field to a ferromagnetic material, the Weiss-domains magnetizations are directed from the initial direction towards the applied field by wall displacement and domain rotation. An estimation has been published which approximately describes the mechanical stress as a function of magnetostriction and magnetization. [11]

$$\sigma = \frac{1}{\mu_r} \cdot \frac{J_s^2}{3\lambda_s \mu_0} \tag{4}$$

where, σ is the mechanical stress, J_s is a magnetic polarization, λ_s is a saturation magnetostriction, μ_r is the permeability of ferromagnetic material, and μ_0 is the permeability of vacuum.

The magnetization of a ferromagnetic material is typically described by the relation between the magnetic field strength (H), and the flux density (B), and it can be expressed by the general constitutive equation.

$$B = \underline{\underline{\mu}} H \tag{5}$$

where, $\underline{\underline{\mu}}$ is the magnetic permeability tensor. However, if the material is macroscopically homogeneous and isotropic, the relation can be reduced to its scalar form and μ is the scalar.

The EM sensor is based on the elasto-magnetic property under the technical magnetic saturation [12]. It consists of a primary coil to magnetize the ferromagnetic material and a secondary coil to measure the induced electromotive force that is directly proportional to the change rate of the applied magnetic field and the relative permeability. Assuming that the magnetic field saturates the ferromagnetic material technically, the relative permeability of the material could be expressed as [13],

$$\mu(\sigma, T) = 1 + \frac{A_0}{A_f}\left[\frac{V_{out}(\sigma, T)}{V_0} - 1\right] \quad (6)$$

where T is the temperature, A_0 is the cross sectional area of the secondary coil, A_f is the cross sectional area of the ferromagnetic material, and V_{out} is the integrated voltage with the ferromagnetic material while V_0 is the integrated voltage without the ferromagnetic material. According to the equation, the tensile force could be estimated by measuring the permeability of the prestressing tendon using an EM sensor.

3 EMBEDDED EM SENSORS

The PS tendon is located inside of PSC girder and it cannot be access in outside of PSC girder. Thus the EM sensor should be embedded into the PSC girder to measure the permeability change of PS tendons. The embedded EM sensor was developed to embed into the PSC girder as shown in figure 1. The whole length of embedded EM sensor was 320 mm and the one side of sensor had screw thread to connect with the sheath and the other side had oblique section to put into the anchor block. The embedded EM sensor was located between sheath and anchor block as a joint using this two parts as shown in figure 2. The coil section has located between joint parts to exclude the magnetization of sheath. The secondary coil that measure the magnetization of PS tendons was coiled the center of sensor and the insulated using insulating cover. The primary coil was winded over the secondary coil and insulated. The turn of secondary coil was 118 turns and the turn of primary coil was 380 turns.

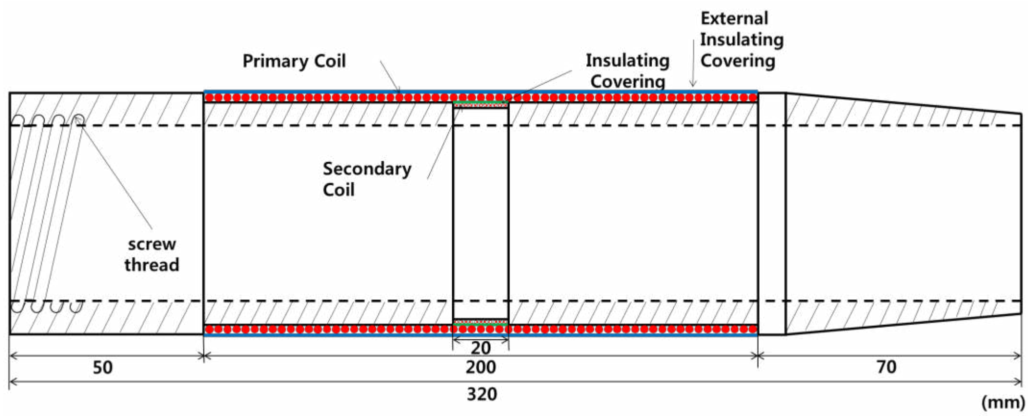


Figure 1: Schematic diagram of embedded EM sensor

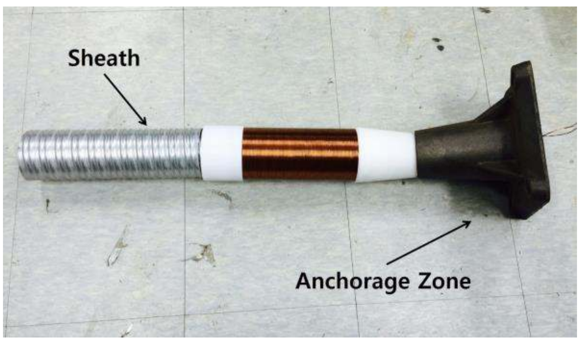
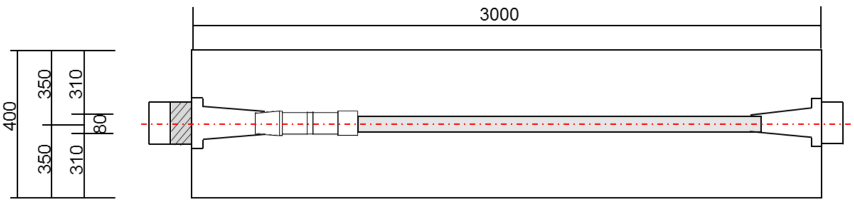


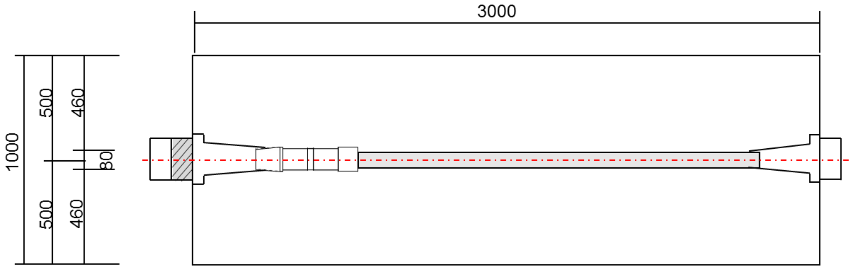
Figure 2: Embedded EM sensor

4 EXPERIMENTAL STUDY

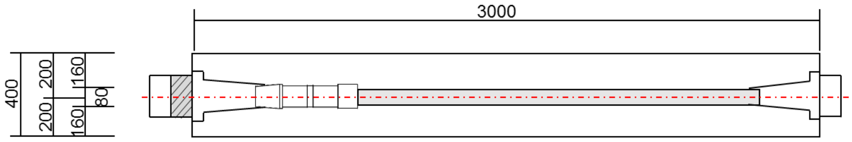
To verify developed embedded EM sensor, the experimental study using three down-scaled PSC girder models was performed. The size of three down-scaled PSC girder model is shown in figure 3. The embedded EM sensor was installed between anchorage block and sheath as shown in figure 4. The concrete was casted and cured during 30 days. After curing, the 7 tendons were installed in down-scaled PSC girder model with load cell to measure the reference tensile forces and the tensile forces was induced step-by-step using multi strand hydraulic jacking device. The tensile force step was 240, 740, 1100 kN for sample 1, 250, 730, 1100 kN for sample 2 and 200, 710, 1074 kN for sample 3. The step force had a small error caused by the hydraulic jacking device. The permeability was measured at each step using embedded EM sensor.



(a) Diagram of sample 1



(b) Diagram of sample 2



(c) Diagram of sample 3

Figure 3: Diagram of test specimens

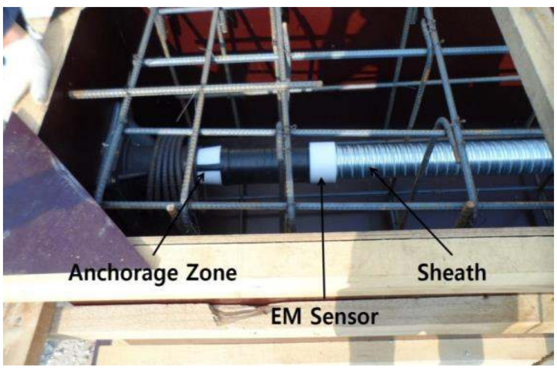


Figure 4: Installation of embedded EM sensor

Figure 5: Concrete casting in test specimen

Figure 6~8 shows the result of permeability change according to the variations in tensile forces. The magnetization was decreased according to the tensile force increasement and also the permeability was decresed. The decreasement of permeability accoring to the tensile force had a pattern in each samples but the permeability of each samples had little difference at similar tensile force. It caused by the difference of initial permeability of each sensors.

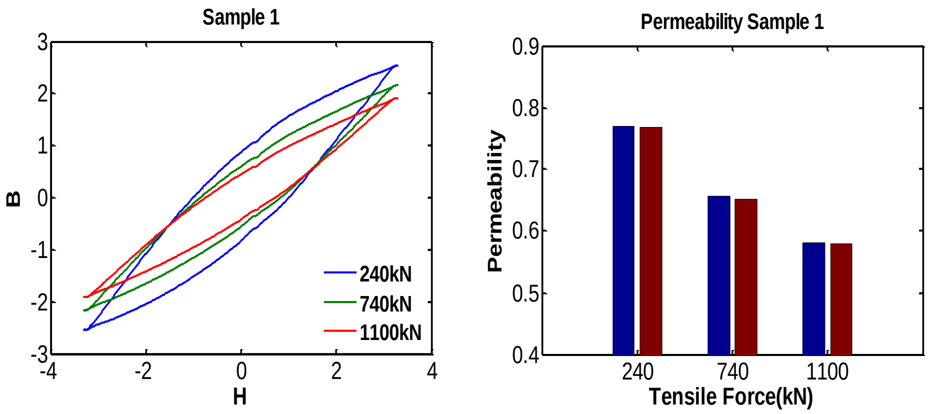


Figure 6: Measurement result of sample 1

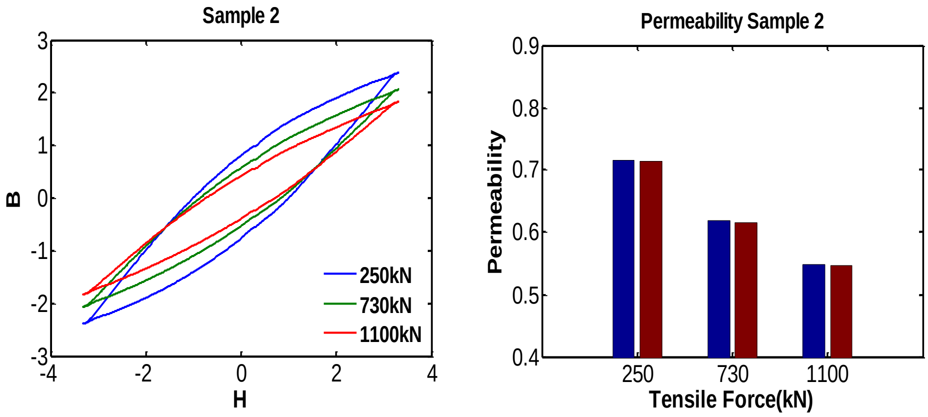


Figure 7: Measurement result of sample 2

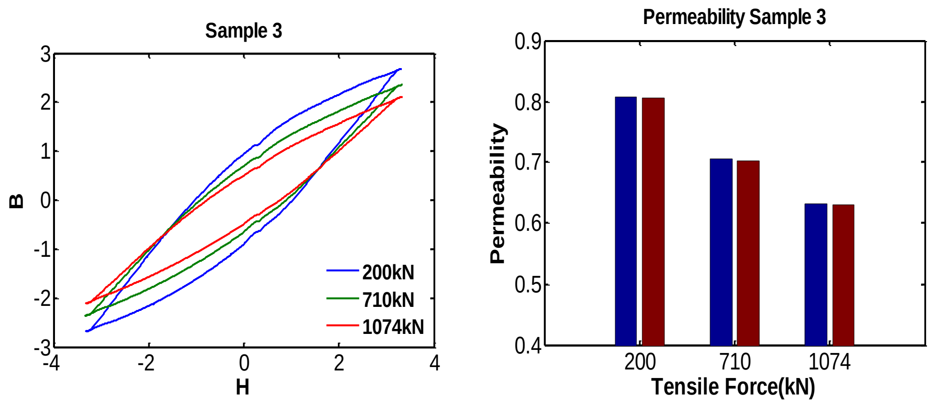


Figure 8: Measurement result of sample 3

To estimate the tensile forces using permeability, the ANN was trained using test data set. The used ANN method was 10-layer feed-forward ANN with back-propagation. The input data was permeability of test data and target data was reference tensile forces measured by load cell. The figure 9 shows the tensile force estimation result using trained ANN. There are some errors under 500kN but it could estimate with negligible error over 500 kN. It could be modified through test data sets using calibrated embedded EM sensors.

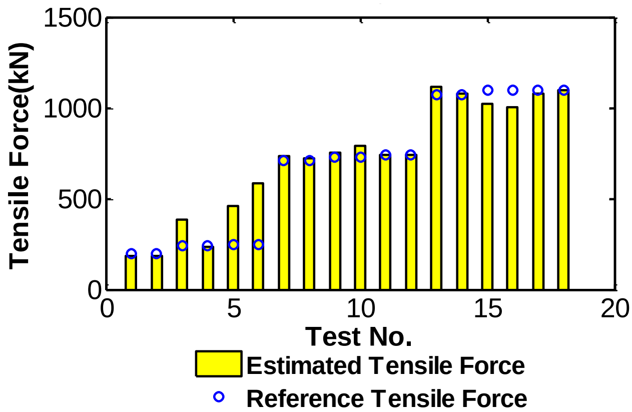


Figure 9: Estimation result using trained ANN

5 CONCLUSIONS

This study proposed tensile force estimation method for PSC girder using embedded EM sensors. The permeability of PS tendon is changed by the induced tensile force, thus the tensile force can be estimate by measuring the permeability change using EM sensor. Because the PS tendon of PSC girder is located inside of PSC girder, typical EM sensors could not be used for PSC girder. To overcome this limitation, this study developed the embedded EM sensor that can be embedded in PSC girder. The embedded EM sensor can install between the anchorage part and sheath as a joint part. The experimental test using three down-scaled PSC girder models was performed to verify the applicability of proposed embedded EM sensor. The embedded EM sensors can measure the permeability changes of PS tendons according to the tensile force change. Furthermore, the ANN for estimating tensile force using permeability was trained and verified by comparing the estimation result and reference tensile force measured by installed load cell. While the ANN can estimate the tensile force over 500 kN with negligible error, it has errors under the 500 kN caused by no calibrated sensor. As a result, the proposed ANN based tensile force estimation for PSC girder using embedded EM sensor could be one of the solution for estimating the tensile force of PSC girder over 500kN.

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